

Quantum Direct Communication with Authentication

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Abstract. We propose two Quantum Direct Communication (QDC) protocols with user authentication. Users can identify each other by checking the correlation of Greenberger-Horne-Zeilinger (GHZ) states. Alice can directly send a secret message to Bob using the remaining GHZ states after authentication. Our second QDC protocol can be used even though there is no quantum link between Alice and Bob. The security of the transmitted message is guaranteed by properties of entanglement of GHZ states.

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1 Introduction

Quantum Cryptography utilizes the original characteristics of quantum mechanics such as superposition, entanglement and so on. Using these properties, some information can be secretly shared between users through a quantum channel. The information can be a key or a message. Quantum Key Distribution (QKD) protocols are used to share a key and Quantum Direct Communication (QDC) protocols are employed to send a message.

Many QKD protocols have been proposed since Bennett and Brassard first proposed a quantum key distribution protocol[1] in 1984. The security of some QKD protocols was theoretically proven in [2–4]. On the other hand, QDC starts to be researched nowadays. First QDC protocol was proposed by Beige et al.[5] in 2002. It was followed by other QDC protocols[6–10].

In most QDC protocols except two protocols proposed by Beige et al. [5] and Deng et al. [6], the receiver(Bob) must begin the protocol to get a secret message from the sender(Alice). For example Bob should generate single photons[7, 8] or Bell states[9] or qutrit states[10] and transmit all or some part of them to Alice. In addition, most QDC protocols are vulnerable to the man in the middle attack.

We propose two QDC protocols, which combine user authentication and direct communication in quantum world at first time. To authenticate users, an authentication method proposed in [11] is introduced. After authentication Alice

can send a secret message directly to Bob. This message may not be leaked to a third party. Moreover Alice and Bob can communicate without a quantum link between them in our second QDC protocol. We present our QDC protocols in the chapter 2, then analyze the security of them in chapter 3 and make conclusions in chapter 4.

2 Quantum Direct Communication Protocols

Our quantum direct communication protocols are composed of two parts: one is an authentication and the other a direct communication. The third party, Trent is introduced to authenticate the users participating in the communication. He is assumed to be more powerful than other users and he supplies the Greenberger-Horne -Zeilinger (GHZ) states[12].

2.1 Authentication

User's secret identity sequence and a one-way hash function are known to Trent. This information must be kept secret between the user and the arbitrator. Suppose Alice's(Bob's) identity sequence and her(his) one-way hash function are $ID_A(ID_B)$ and $h_A(h_B)$, respectively. For example, a one-way hash function is $h : \{0, 1\}^* \times \{0, 1\}^c \rightarrow \{0, 1\}^l$, where $*$ is arbitrary length, c the length of a counter and l a fixed number. Alice's(Bob's) authentication key shared with Trent can be calculated as $h_A(ID_A, c_A)(h_B(ID_B, c_B))$, where $c_A(c_B)$ is the counter of calls on Alice's(Bob's) hash functions. Authentication keys are used to determine unitary operations on GHZ particles heading from the arbitrator to the owner. Users can authenticate each other by checking the correlation of the GHZ states taken the reverse unitary operations.

If Alice wants to send a secret message to Bob, she notifies this fact to Bob and Trent. On receiving the request, Trent generates N GHZ tripartite states $|\Psi\rangle = |\psi_1\rangle \dots |\psi_N\rangle$. For simplicity the following GHZ state $|\psi_i\rangle$ is supposed to be prepared.

$$|\psi_i\rangle = \frac{1}{\sqrt{2}}(|000\rangle_{ATB} + |111\rangle_{ATB})$$

where the subscripts A, T and B correspond to Alice, Trent, and Bob, respectively. In this paper, we represent the z basis as $\{|0\rangle, |1\rangle\}$ and the x basis as $\{|+\rangle, |-\rangle\}$, where $|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ and $|-\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$.

Next, Trent encodes Alice's and Bob's particles of GHZ states with their authentication keys, $h_A(ID_A, c_A)$ and $h_B(ID_B, c_B)$, respectively. For example, if the i th value of $h_A(ID_A, c_A)$ (or $h_B(ID_B, c_B)$) is 0, then Trent makes an identity operation I to Alice's (Bob's) particle of the i th GHZ state. If it is 1, Hadamard operation H is applied. If the authentication key $h_A(ID_A, c_A)$ (or $h_B(ID_B, c_B)$) does not have enough length to cover all GHZ particles, new authentication keys can be created by increasing the counter until the authentication keys shield all GHZ particles. After making operations on the GHZ particles, Trent distributes the states to Alice and Bob and keeps the remaining for him.

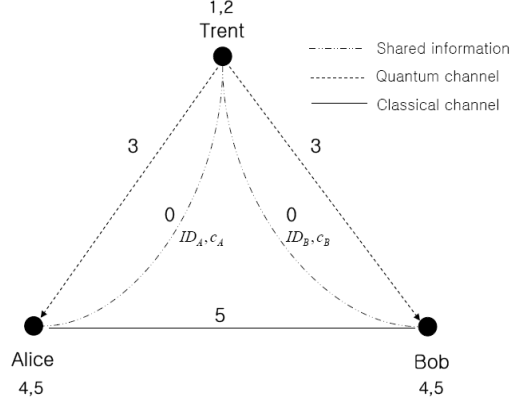


Fig.1. Procedures of Authentication 0. Alice and Bob register their secret identity and hash functions to Trent, respectively. 1. Trent generates GHZ states $|\psi\rangle = \frac{1}{\sqrt{2}}(|000\rangle_{ATB} + |111\rangle_{ATB})$. 2. Trent makes unitary operations on $|\psi\rangle$ with Alice's and Bob's authentication key. 3. Trent distributes GHZ particles to Alice and Bob. 4. Alice and Bob make reverse unitary operations on their qubit with their authentication key, respectively. 5. Alice and Bob choose the position of a subset of GHZ states and make a local measurement in the z basis on them and compare the results.

On receiving the qubits, Alice and Bob decode the qubits with unitary transformations which are defined by their authentication keys, $h_A(ID_A, c_A)$ and $h_B(ID_B, c_B)$, respectively. Next, Alice and Bob select some of the decoded qubits, make von-Neumann measurements on them, and compare the results through the public channel. If the error rate is higher than expected, then Alice and Bob abort the protocol. Otherwise they can confirm that the other party is legitimate and the channel is secure. They then execute the following message transmission procedures.

2.2 Direct Communication Protocol 1

Alice selects a subset of GHZ states in the remaining sets after authentication and keeps it secret. Alice chooses a random sequence which has no connection with the secret message to transmit to Bob. Following this random sequence, Alice performs unitary transformations on the qubits selected for this check process. Before encoding the message and the random sequence, Alice can encode the secret message with a classical Error Correction Code (ECC) such as the Hamming Code, the Reed-Solomon code and the BCH code, so that Bob could be able to correct errors in the decoded message. For example, if the error rate of the quantum channel is 20% and the length of codeword is n , then any classical ECCs can be used, where the minimum length of the code d is larger than $\lfloor \frac{2n}{5} \rfloor + 1$. If the bit of the random sequence, or the message is 0, then Alice performs on her GHZ particle with Hadamard operation H . Otherwise, Alice

acts at her qubit with first Bit flip operation X and then Hadamard operation H . After making all unitary operations, Alice transfers all encoded qubits to Bob.

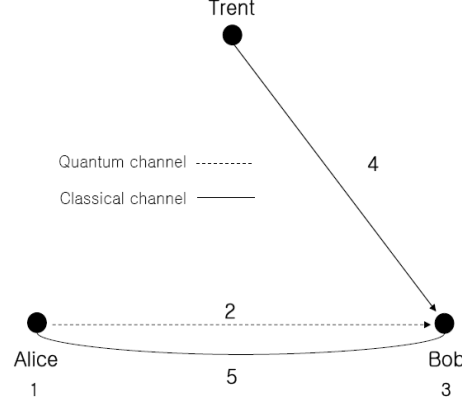


Fig. 2. Procedures of the first Direct Communication protocol 1. Alice chooses a subset of GHZ states and a random sequence. Alice performs unitary transformation both on the qubits selected for this check process following this random sequence and on the remaining qubits following the secret message. For example if the bit is 0, she makes a Hadamard operation H , otherwise a bit flip operation and a Hadamard operation HX . 2. Alice sends the qubits to Bob. 3. Bob makes Bell measurements on pairs of particles consisting of his qubits and Alice's qubit. 4. Trent makes von Neumann measurements on his GHZ particles and reveals the results. 5. Alice and Bob compare the check bits.

Bob makes Bell measurements on pairs of particles consisting of his qubit and Alice's qubit. In this paper we use the following notations of Bell states.

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}\{|00\rangle + |11\rangle\}$$

$$|\Phi^-\rangle = \frac{1}{\sqrt{2}}\{|00\rangle - |11\rangle\}$$

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}\{|01\rangle + |10\rangle\}$$

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}\{|01\rangle - |10\rangle\}$$

Trent measures his third qubit in the x basis and publishes the measurement outcomes. Bob recovers Alice's message using the table [1]. For example, if Bob measures $|\Phi^+\rangle$ and Trent reveals $|+\rangle$, then Bob can infer Alice made HX operation and she sent 1.

Table 1. Operations on the decrypted GHZ state(i.e. $|\psi\rangle$) and Transformation of the GHZ state

Alice's Operation	Transformation of GHZ states after Alice's operation
$H(0)$	$\frac{1}{2}(\Phi^+\rangle_{AB} - \rangle_T + \Phi^-\rangle_{AB} + \rangle_T + \Psi^+\rangle_{AB} + \rangle_T - \Psi^-\rangle_{AB} - \rangle_T)$
$HX(1)$	$\frac{1}{2}(\Phi^+\rangle_{AB} + \rangle_T + \Phi^-\rangle_{AB} - \rangle_T - \Psi^+\rangle_{AB} - \rangle_T + \Psi^-\rangle_{AB} + \rangle_T)$

After obtaining all messages, Bob notifies this fact to Alice. Alice reveals the position of the check bits and compares the bits with Bob. If the error rate is higher than expected, Alice and Bob conclude there was an eavesdropper. The message contains errors, but fortunately Eve cannot know its content. Otherwise Bob can extract the secret message from the remaining bits.

2.3 Direct Communication Protocol 2

The second QDC protocol is same as the first protocol except Alice sends her encoded qubits to the Trent. However it is not needed additional quantum link between Alice and Bob in this protocol. After making Bell measurement on his and Alice's qubits, Trent reveals the result. If $|\Phi^+\rangle$ or $|\Psi^-\rangle$, then Trent publishes 0. Otherwise he notifies 1. Bob measures his particles on the X basis. (This process of Bob can be preceded even before the Alice's operation.) Using the Trent's publication and his measurement, Bob can infer which operations were used by Alice as shown in the table [2]. If 0 is published and $|+\rangle$ is measured, Bob can discover Alice operated HX (1).

Table 2. Operations on the decrypted GHZ state(i.e. $|\psi\rangle$) and Transformation of the GHZ state

Alice's Operation	Transformation of GHZ states after Alice's operation
$H(0)$	$\frac{1}{2}(\Phi^+\rangle_{AT} - \rangle_B + \Phi^-\rangle_{AT} + \rangle_B + \Psi^+\rangle_{AT} + \rangle_B - \Psi^-\rangle_{AT} - \rangle_B)$
$HX(1)$	$\frac{1}{2}(\Phi^+\rangle_{AT} + \rangle_B + \Phi^-\rangle_{AT} - \rangle_B - \Psi^+\rangle_{AT} - \rangle_B + \Psi^-\rangle_{AT} + \rangle_B)$

Alice reveals the position of her check bits and compares them with Bob. If the error rate of the check bits is higher than expected, Bob throws away the message. Otherwise, Bob can get the whole secret by applying the classical ECC code used by Alice if it was used.

3 Security Analysis

The security of our protocol results from the properties of the entanglement of GHZ states. We first analyze the process of authentication. If Trent is honest,

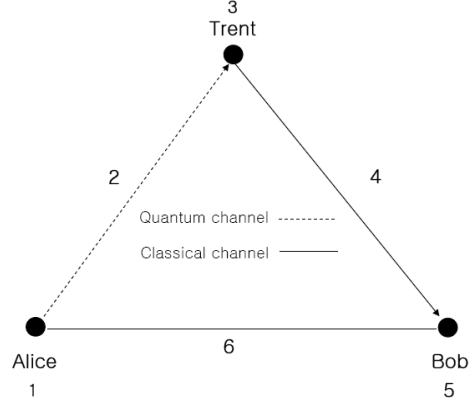


Fig.3. Procedures of the second Direct Communication protocol 1. Alice chooses the position of check bits and a random sequence. Alice performs unitary transformation on the qubits selected for this check process following this random sequence and on the remaining qubits following the secret message. For example if the bit is 0, she makes a Hadamard operation H , otherwise a bit flip operation and a Hadamard operation HX . 2. Alice sends the encoded qubits to Trent. 3. Trent makes Bell measurements on pairs of particles consisting of his qubits and Alice's qubit. 4. Trent reveals the measurement outcomes. 5. Bob makes von Neumann measurements on his GHZ particles. 6. Alice and Bob compare the check bits.

then he will generate tripartite GHZ states, encrypt them with the right authentication keys and then distribute them to the designated users. Only the designated user can decrypt the qubits to recover the original GHZ states. This procedure can be written in the following form of a sequence of local unitary operation, the initial state:

$$|\psi_i\rangle_1 = \frac{1}{\sqrt{2}}(|000\rangle_{ATB} + |111\rangle_{ATB})$$

state after Trent's transformation

$$\begin{aligned} |\psi_i\rangle_2 &= \{[1 - f_A(ID_A, c_A)]I + [f_A(ID_A, c_A)]H\}_A \\ &\otimes \{[1 - f_B(ID_B, c_B)]I + [f_B(ID_B, c_B)]H\}_B |\psi_i\rangle_1 \end{aligned}$$

and finally the state after Alice's and Bob's local operations

$$\begin{aligned} |\psi_i\rangle_3 &= \{[1 - f_A(ID_A, c_A)]I + [f_A(ID_A, c_A)]H\}_A \\ &\otimes \{[1 - f_B(ID_B, c_B)]I + [f_B(ID_B, c_B)]H\}_B |\psi_i\rangle_2 \\ &= |\psi_i\rangle_1 \end{aligned}$$

where $|\psi_i\rangle$ is the state of the i -th GHZ particle and the subscript 1, 2, and 3 represents the three steps of authentication. Of course, such is the situation

if there is no Eve. Suppose Eve intercepts the qubits heading to Alice or Bob and disguises her or him. Eve can be detected with probability $1/4$ per check bits in this authentication process since she does not know Alice's or Bob's authentication key.

Let an attacker, Eve, use a coherent attack. She then causes errors per check bit with a probability $1/4$ similarly to BB84 protocol if she uses the original bases used by Alice and Bob. It is because Eve didn't know the authentication key and she cannot decrypt the encoded qubits. For example, if the authentication key bit is 0, Eve doesn't make error in the qubit. Otherwise, an error occurs with probability $1/2$. If Eve prepares $|0\rangle$ state and entangles with Alice's qubit, then the final state of the protocol qubit and Eve's qubit is after decoding by Alice and Bob as follows.

$$\begin{aligned} |\psi'\rangle_{ATBE} &= U_{AE}|\psi\rangle_{ATB} \otimes |0\rangle_E \\ &= \frac{1}{2}\{|000\rangle_{ATB}|+\rangle_E + |100\rangle_{ATB}|-\rangle_E + |011\rangle_{ATB}|-\rangle_E + |111\rangle_{ATB}|+\rangle_E\} \end{aligned}$$

This is for a specific attack where $U_{AE}|0\rangle_A|0\rangle_E \rightarrow |0\rangle_A|0\rangle_E$ and $U_{AE}|1\rangle_A|0\rangle_E \rightarrow |1\rangle_A|1\rangle_E$. Eve can be detected with higher probability $1/2$ per check bit in this case. Hence, if $m(\ll N)$ GHZ states are checked in the authentication process, Alice and Bob can confirm that the GHZ states are distributed to the legitimate users with probability $1 - (\frac{3}{4})^m$. We expect more advanced attack can be detected when m is increased.

After authentication process, only Alice's qubits are transmitted. Eve will make operations on these qubits in our quantum direct communication protocols. In both protocols, Eve must not be disclosed during the authentication process to obtain any information of secret message. Suppose Eve use the following unitary operation U_{AE} on Alice's and her qubit $|E\rangle$.

$$U_{AE}|0E\rangle_{AE} = \alpha|0\rangle_A|e_{00}\rangle_E + \beta|1\rangle_A|e_{01}\rangle_E$$

$$U_{AE}|1E\rangle_{AE} = \beta'|0\rangle_A|e_{10}\rangle_E + \alpha'|1\rangle_A|e_{11}\rangle_E$$

where $|\alpha|^2 + |\beta|^2 = 1$, $|\alpha'|^2 + |\beta'|^2 = 1$ and $\alpha\beta^* + \alpha'^*\beta' = 0$.

Then the state of the protocol is changed as follows.

- 1 The states after Alice made a unitary operation

$$\begin{aligned} |\psi_1\rangle_{ATBE} &= U_A|\psi\rangle_{ATB} \otimes |E\rangle_E \\ &= \frac{1}{2}(|000\rangle_{ATB} \mp |100\rangle_{ATB} + |011\rangle_{ATB} \pm |111\rangle_{ATB}) \otimes |E\rangle_E \end{aligned}$$

- 2 The states after Eve made a unitary operation on her qubit and Alice's qubit heading to Bob or Trent

$$\begin{aligned} |\psi_2\rangle_{ATBE} &= U_{AE}|\psi_1\rangle_{ATBE} \\ &= \frac{1}{2}\left\{|000\rangle_{ATB}(\alpha|e_{00}\rangle \pm \beta'|e_{10}\rangle)_E + |100\rangle_{ATB}(\beta|e_{01}\rangle \pm \alpha'|e_{11}\rangle)_E \right. \\ &\quad \left. + |011\rangle_{ATB}(\alpha|e_{00}\rangle \mp \beta'|e_{10}\rangle)_E + |111\rangle_{ATB}(\beta|e_{01}\rangle \mp \alpha'|e_{11}\rangle)_E\right\} \\ &= \frac{1}{2\sqrt{2}}\left[\Phi_{AB}^+\left\{|+\rangle_T(\alpha|e_{00}\rangle \pm \beta'|e_{10}\rangle + \beta|e_{01}\rangle \mp \alpha'|e_{11}\rangle)_E \right. \right. \\ &\quad \left. \left. + |-\rangle_T(\alpha|e_{00}\rangle \pm \beta'|e_{10}\rangle - \beta|e_{01}\rangle \pm \alpha'|e_{11}\rangle)_E\right\} \right. \\ &\quad \left. + \Phi_{AB}^-\left\{|+\rangle_T(\alpha|e_{00}\rangle \pm \beta'|e_{10}\rangle - \beta|e_{01}\rangle \pm \alpha'|e_{11}\rangle)_E \right. \right. \end{aligned}$$

$$\begin{aligned}
& + |-\rangle_T (\alpha|e_{00}\rangle \pm \beta'|e_{10}\rangle + \beta|e_{01}\rangle \mp \alpha'|e_{11}\rangle)_E \Big\} \\
& + \Psi_{AB}^+ \Big\{ |+\rangle_T (\alpha|e_{00}\rangle \mp \beta'|e_{10}\rangle + \beta|e_{01}\rangle \pm \alpha'|e_{11}\rangle)_E \\
& \quad - |-\rangle_T (\alpha|e_{00}\rangle \mp \beta'|e_{10}\rangle - \beta|e_{01}\rangle \mp \alpha'|e_{11}\rangle)_E \Big\} \\
& + \Psi_{AB}^- \Big\{ |+\rangle_T (\alpha|e_{00}\rangle \mp \beta'|e_{10}\rangle - \beta|e_{01}\rangle \mp \alpha'|e_{11}\rangle)_E \\
& \quad - |-\rangle_T (\alpha|e_{00}\rangle \mp \beta'|e_{10}\rangle + \beta|e_{01}\rangle \pm \alpha'|e_{11}\rangle)_E \Big\} \Big]
\end{aligned}$$

As shown in the above equations, Eve will introduce errors in the check bits with the probability of $1/2$ regardless of the order of measurement by Bob, Trent and Eve. Moreover, Eve cannot get any information from this attack since Eve cannot distinguish the two cases which Alice made operation H or HX . For example, suppose Alice makes operation $H(0)$, Bob measures $|\Psi^+\rangle$, and Eve measures $|e_{00}\rangle$. Then Trent will reveal $|+\rangle$ or $|-\rangle$ with equal probability. If Trent reveals $|+\rangle$ then Bob can revoke correct information. Otherwise Bob can find an error. Hence if the length of the check sequence is long enough, then we can find the existence of Eve in the transmission of message and confirm Eve does not intercept the message.

4 Conclusions

We have proposed two Authenticated Quantum Direct Communication protocols. After identifying the other user in the communication channel, Alice can directly send a secret message to Bob without a previously shared secret key. According to the existence of a quantum link between Alice and Bob, they can choose a QDC protocol between two. If there exists eavesdropping during transmission, the message will be broken and Alice and Bob can ascertain the existence of Eve by the check-bits. Though the message was broken, Eve cannot get any information of the secret message. We expect our schemes can be applied well to quantum networks even in a transition period.

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